ACOUSTICAL EMISSION FROM BUBBLES

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SCIENTIFIC OBJECTIVES

To investigate the dynamics of bubbles formed from a free surface (particularly the upper surface of the ocean) by breaking waves, and the resulting emission of underwater sound.

BACKGROUND

The chief natural source of underwater sound in the ocean at frequencies from 0.5 to 50 kHz is known to be the acoustical emission from newly-formed bubbles and bubble clouds, particularly those created by breaking waves and rain. With individual bubbles, the emission occurs in the first few milliseconds after bubble formation. The process of bubble formation and the dynamics of the resulting oscillations are not completely understood. In last year's Progress Report (see also Ref. 1 below) attention was drawn to the occurrence of high-speed jets directed into the bubble just after bubble closure. They have been observed both in rain-drop impacts and in the release of bubbles from an underwater nozzle (Ref. 1). Qualitatively they are similar to the inward jets seen in the collapse of a cavitation bubble. There is also a similarity to the highly-accelerated upward jets in standing water waves (accelerations > 20g) or in bubbles bursting at a free surface.

The process of air entrainment at a free surface in light winds is also not understood. This seems to be associated with parasitic capillary waves on the forward face of gravity waves, without either plunging or spilling. In short gravity waves (0.1m to 1m) there is also an unexplained "roller", or concentration of vorticity at the wave crest, not present in the rest of the wave (Ebuchi et al 1987). This is sometimes associated with air entrainment (Koga, 1982).

APPROACH

We have adopted a theoretical approach based on the dynamics of incompressible fluids with a free surface. As is well known, the problems are highly nonlinear. Useful results on bubble dynamics can be obtained by using a boundary-integral method for numerical computations of the flow. However, for a deeper understanding of the phenomena, analytical solutions are highly desirable, if only they can be obtained. We have sought both types of description, with some success.

PROGRESS

Progress has been made in two main directions. The first is the discovery of a new class of highly-accelerated flows with a free surface, which seem to describe the inward-directed jets seen in bubble generation and collapse. An example is shown in Figure 1a. The flow is given by the surprisingly simple expression

$$x + iy = (F_1 \sin \omega \ - i\, G_1 \cos \omega) + \frac{1}{2}\,(F_2 \sin 2\omega \ - i\, G \cos 2\omega) \qquad (1)$$

where ω is a complex parameter, real at the free surface. The coefficients F_1, G_1, F_2 and G_2 are real functions of the time t only, related by a set of nonlinear, ordinary differential equations, so as to satisfy appropriate boundary conditions and conditions of regularity in the fluid. A wide variety of such flows exists, depending on the initial conditions. One remarkable feature of many of the flows is the occurrence of a sudden "inertial shock" at a certain instant. This usually happens when the surface locally has the form of a rectangular hyperbola - as in the previously known "Dirichlet hyperbola" (*J. Fluid Mech.*, **127**, 103, 1983). The phenomenon is illustrated by the behaviour of the inwards acceleration y_{tt} at the point $\omega = 0$ on the free surface (the tip of the jet); see Figure 1b. The acceleration becomes infinite like $(t - t_0)^{-1}$, near the instant $t_0 = 0.1502$.

Solutions also exist with two jets directed inwards from opposite sides of the bubble - or indeed any number of such jets per bubble.

So far the solutions obtained are for two-dimensional flows, that is to say cylindrical bubbles or cavities. Corresponding flows with axial symmetry are being sought. There, the jets may be expected to be even stronger, on account of the axial convergence of the flow.

The implications for generating underwater sound are interesting and need to be further investigated. If further terms are added to the above solutions, the infinite peaks are expected to become bounded, but still large. Nevertheless, each such "kick" can be expected to generate a broad-band acoustical signal.

The above flows were discovered in a somewhat indirect way, through a (successful) attempt to find a model for the highly accelerated jets ($y_{tt} > 20g$) sometimes ob-

served in standing gravity waves with axial symmetry (Longuet-Higgins 1983) and in two-dimensional waves interacting with a vertical wall (Peregrine and Cooker 1990). A full account is given in Ref. 6 below.

Numerical calculations of bubble oscillations following detachment from a free surface have been carried out by Dr. H. Oguz and the present investigator, using initial flow conditions derived from the theory of steep capillary waves (see Ref. 2). These calculations also show the occurrence of inward jets in some cases.

Following publication of work with B.R. Kerman and K. Lunde on the release of bubbles from an underwater nozzle (Ref. 1) the author and K. Lunde obtained further high-speed photographs of bubble splitting and spin-off following the main release. These observations are in process of analysis.

The second main direction of my research has been towards understanding the nonlinear dynamics of short gravity waves (wavelengths 0.1 to 1 m) which develop strong vortices at the crest immediately prior to breaking. In Ref. 5 I have shown that this vorticity is generated mainly by the "parasitic" capillary waves which are seen just ahead of the crest of the gravity wave. There is also a feedback between the crest roller and the capillary waves, so that the phenomenon is self-sustaining: a capillary "bore". The leading capillary waves can be steep enough to trap air bubbles. At larger scales the capillaries are over-ridden and a free shear-layer is formed.

PUBLICATIONS

1. Longuet-Higgins, M.S., Kerman, B.R. and Lunde, K. 1991. "The release of air bubbles from an underwater nozzle." *J. Fluid Mech.*, **230**, 365-390. See also *J. Acoust. Soc. Amer.*, **89**, 2014 (Abstract).

2. Oguz, H.N. and Longuet-Higgins, M.S. 1991. "Dynamics of air bubbles entrapped by capillary waves." *J. Acoust. Soc. Amer.* **89**, 2014-2015 (Abstract).

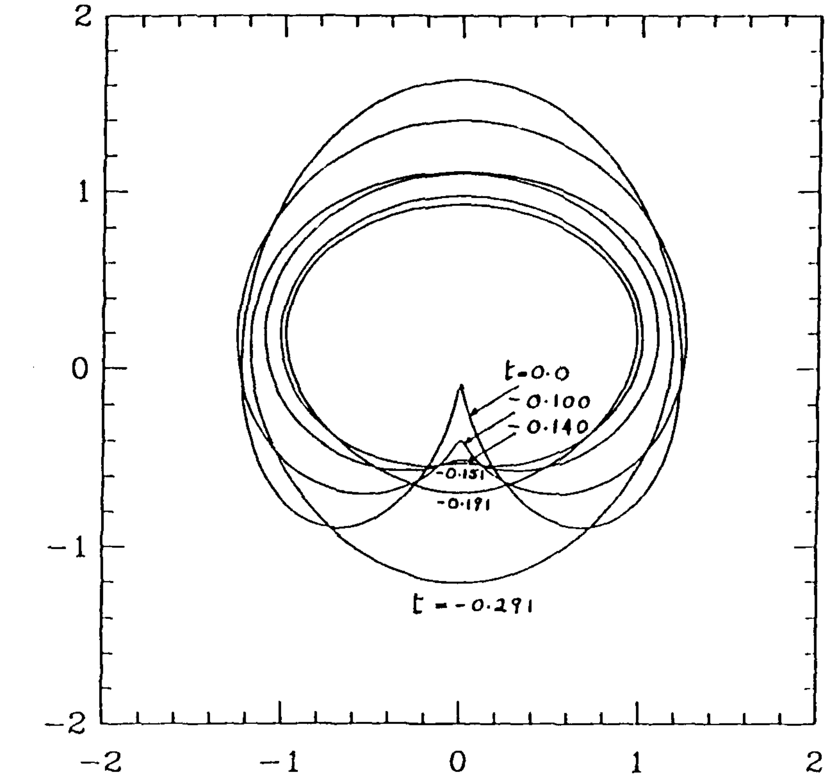
3. Longuet-Higgins, M.S. 1992. "Nonlinear damping of bubble oscillations by resonant interaction." *J. Acoust. Soc. Amer.*, **91**, 1414-1422.

4. Longuet-Higgins, M.S. 1992. "Capillary rollers." *Proc. IUTAM Symp. on Breaking Waves*, Sydney, Australia, 15-19 July 1991. Berlin, Springer (to appear).

5. Longuet-Higgins, M.S. 1992. "Capillary rollers and bores." *J. Fluid Mech.* (Accepted for publication).

6. Longuet-Higgins, M.S. 1992. "Highly-accelerated, free-surface flows." (Submitted to *J. Fluid Mech.*).

7. Longuet-Higgins, M.S. 1992. "Asymmetric collapse of a cylindrical cavity." (In preparation).



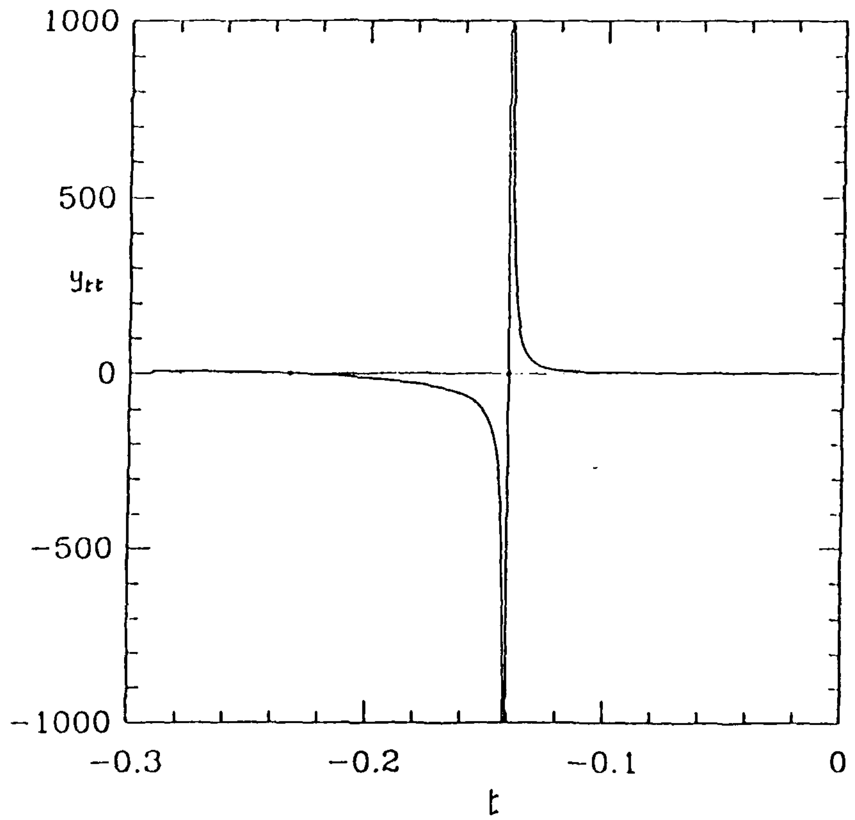


Figure 1a. Successive profiles of a cylindrical cavity during asymmetric collapse, as described by equation (1).

Figure 1b. The acceleration y_{tt} at the tip of the jet shown as a function of the time t.